frequency, and let Δf be the shift of the first harmonic cavity frequency, then it is found that $\Delta\nu=\alpha\gamma T_c\Delta f$, where γ is the hyperfine linewidth, T_c is the cavity round-trip time, and α is a factor determined by the length of the vapor cell and the vapor density.

Self-modulated laser system **50** uses polarization-diverse gain medium **52**. Light with any polarization can be amplified by this type of gain medium. Polarization diverse gain medium can be made by electronically pumped semiconductors, such as, for example, ELDs and vertical cavity surface emitting laser (VCSEL) diodes. Accordingly, this embodiment does not use quarter wave plates on either side of the vapor cell to achieve the light pumping pattern as shown in FIG. **6**. The combination of a quarter wave plate and a linear polarizer is for the photodetector to detect light with the photon spin of only s=1 or only s=−1. The commensuration of the cavity mode to the hyperfine frequency is used.

Self-modulated laser system **60** uses ring cavity **61**. In this embodiment, photons are moving to one direction. Polarization-diverse gain medium **62** is used for generating the pumping pattern shown in FIG. **6**. Narrow band optical filter **64** inside cavity **61** operates in a similar manner as the Bragg mirror described above for other configurations. Only the laser light in the frequency range of narrow band optical filter **64** is allowed to circulate in ring cavity **61**. The cycling period of ring cavity **61** is about a multiple of the hyperfine period. This embodiment has the advantage of having the least cavity-pulling effect, since the alkali-metal vapor is filled inside the entire cavity.

Self-modulated laser system **70** uses gain medium **42**, vapor cell **44**, Bragg mirror **45**, and output coupler **46** compacted together. The cavity length is much shorter so that the round-trip time is much less than the hyperfine period. In this embodiment, the generation of the push-pull pumping light relies on the intrinsic property of the gain medium. For example, by using a four-level diagram to describe the optical transitions of the gain medium, the amplifications of $\sigma+$ and $\sigma-$ light depend on two different optical transitions, which have the difference of azimuthal quantum number $\Delta m=+1$ and $\Delta m=-1$. By a proper design of the relaxation properties of the spin-dependent quantum levels of the gain medium, the spontaneous push-pull pumping can be established. An advantage of this embodiment is the very compact size of the self-modulated laser system, since the cavity length is not limited by the hyperfine frequency. With a proper design of the semiconductor gain medium and the miniature laser cavity, a millimeter or sub-millimeter scale photonic clock (without local oscillator) can be achieved.

It is appreciated that the cavity configurations shown in FIGS. **7**A-**7**D are only for examples. Other types of cavity design that realize the self modulation of the laser beam into the optical comb by using alkali-metal vapor cell is considered to be within the teachings of the present invention.

FIG. **8**, FIG. **9**, and FIG. **10**, show the results of computer simulations of the self-modulated laser system of FIG. **7**A. There are three panels for each figure, and the horizontal axis is the increase of time. The top panel shows the relative carrier density inside the EDL as a function of time. The middle panel shows the laser intensity inside the cavity as a function of time. The bottom panel shows the electron-spin amplitude due to the 0-0 hyperfine coherence along the z-direction as a function of time. For FIG. **8**, it is assumed that the vapor cell contains ^{87}Rb with 3 atm buffer-gas pressure. The gain bandwidth is about 66 GHz. The beam diameter is 3 mm. The purity of photon spin is 90%. The loss from the output coupler is 30%. The vapor cell has optical thickness of 0.1 e-folding. Initially, a small spin oscillation is observed in the scale of 10^{-8} due to the stepping up laser intensity when laser just turns on. The spin oscillation cannot maintain and die away because of the insufficient vapor density. By increasing the optical thickness of the vapor cell to 0.25 and remaining other conditions the same, it was found that a strong spin oscillation building up in about a millisecond after turning on the laser, and the light is also modulated at the hyperfine frequency as shown in FIG. **9**. FIG. **10** shows one of the simulation results for ^{133}CS. Cesium has high nuclear spin than rubidium. It requires high vapor density to generate spontaneous push-pull pumping inside the cavity. If the optical thickness is increased to 0.5, e-folding, and the beam diameter is reduced to 1 mm. Spontaneous push-pull pumping starts in about 0.1 millisecond after turning on the laser. For all simulations described above, the tolerance of the mismatching between the cavity mode and the hyperfine frequency is about 0.5%. Beyond the tolerance, spontaneous push-pull pumping cannot be produced.

FIG. **11** illustrates the intensity pattern along the cavity axis at different time points when a steady self modulation is built up. In this simulation, the round-trip time of the cavity is equal to three times hyperfine period. The vapor cell is placed at the center of the laser cavity. It is shown that each time the light pulse hits the vapor cell, there is maximum spin magnitude. The laser continuously outputs light pulse repeating at the hyperfine frequency. The light pulse signal can be easily converted into an electrical ticking signal as a clock. For using the self-modulated laser as the atomic clock, the gain medium and the vapor cell have to be temperature stabilized; the ambient magnetic field of the laser cavity has to be stabilized; the cavity length also has to be stabilized. The stabilization of magnetic field and the temperature can be achieved by using a magnetic-field sensor and a temperature sensor with two feedback loops to compensate the changes of those two quantities. The cavity length can be stabilized by a feedback adjustment of the cavity length to obtain a maximum light modulation.

FIG. **12** shows results of a computer simulation of the self-modulated laser system **70** of FIG. **7**D. The vapor cell is assumed to have ^{85}Rb. The effective cavity round-trip time is 5 ps, which is much shorter than the hyperfine period, ~330 ns, of ^{85}Rb. It is shown in FIG. **12** that the self-modulated laser light is alternating between $\sigma+$ polarization (solid line) and σ-polarization (dotted line). The generation of spontaneous push-pull pumping inside the vapor cell strongly depends on some physical parameters of the laser diode, such as the differential gain, the carrier lifetime, the excited-state spin relaxation rate of the gain medium, and the carrier pumping rate.

It is to be understood that the above-described embodiments are illustrative of only a few of the many possible specific embodiments, which can represent applications of the principles of the invention. Numerous and varied other arrangements can be readily devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A method for operating a self-modulated laser comprising:

providing one or more photonic gain media and a vapor cell within a laser cavity; and